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Automatic Adjustments of a Trans-oesophageal Ultrasound Robot for Monitoring Intra-operative Catheters

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Automatic Adjustments of a Trans-oesophageal Ultrasound Robot for Monitoring Intra-operative Catheters

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Abstract. 3D trans-oesophageal echocardiography (TOE) has become a powerful tool for monitoring intra-operative catheters used during cardiac procedures in recent years. However, the control of the TOE probe remains as a manual task and therefore the operator has to hold the probe for a long period of time and sometimes in a radiation environment. To solve this problem, an add-on robotic system has been developed for holding and manipulating a commercial TOE probe. This paper focuses on the application of making automatic adjustments to the probe pose in order to accurately monitor the moving catheters. The positioning strategy is divided into an initialization step based on a pre-planning method and a localized adjustments step based on the robotic differential kinematics and related image servoing techniques. Both steps are described in the paper along with simulation experiments performed to validate the concept. The results indicate an error less than 0.5 mm for the initialization step and an error less than 2 mm for the localized adjustments step. Compared to the much bigger live 3D image volume, it is concluded that the methods are promising. Future work will focus on evaluating the method in the real TOE scanning scenario.

1. Introduction

Catheter-based procedures for minimally invasive surgeries have been widely used in the last two decades as a replacement for open-surgery to treat various types of heart disease. In these procedures, catheters are inserted into a large vein through a small incision, made usually in the groin area, and then are advanced into the heart. With the development in recent years of real-time three-dimensional (3D) ultrasound, guiding of catheter-based procedures can be performed using a 3D TOE probe [1] and this approach has been gradually investigated by more organizations ever since the first experience reported by Perk *et al* [2]. 3D TOE has its unique advantage in visualizing catheters and 3D heart structures due to its volumetric imaging nature [3]. Studies have also indicated that the entire scenario including the catheter, devices, and heart structures (e.g. septum, valve, and appendage) in most catheter-based procedures can be imaged in a single 3D view [4]. Because of this, 3D TOE has great potential to be used more widely in the future for guiding catheter-based procedures and researchers have already started pursuing standardized 3D protocols for specific procedures [5]. Despite the advancement of the imaging techniques, 3D TOE is still a manually controlled approach where a skilled operator is required to hold and manipulate the probe. This is tedious and harmful for the duration of the longer interventional procedures, especially when TOE is used in conjunction with X-ray. Heavy protection clothes and long periods of standing are required which can lead to several occupational diseases [6]. Considering these challenges, we designed an add-on robotic system [7] which allows remote control of a commercial TOE probe (x7-2t, Philips, The Netherlands). The robot has four degrees-of-freedom (DOFs), which allow the translation and rotation of the probe shaft, as well as the bi-directional bending of the probe head.

In this paper, we propose a new concept using the designed TOE robot to automatically monitor intra-operative catheters and place the catheter in the centre of the Field of view (FOV). To our knowledge, the device we designed is the first published system for robotically manipulating a TOE probe. The automatic positioning of the probe for catheter monitoring is a unique topic which has not been reported before, although detailed methods employed in this paper are related to research works for other types of endoscopes in different applications, such as described in [8, 9]. The automatic adjustments of the probe are done by a pre-planning method for initialization and a numerical servo loop based on differential kinematics for localized adjustments. This paper focuses on reporting the detailed methods relating to the robotic automation and presents simulation studies for the validation. Details of the related existing image processing methods will not be discussed in detail.

2. Overview of the robotic TOE system

The developed add-on TOE robot (figure 1a) holds the probe handle and manipulates four mechanical DOFs that are available in manual handling of the probe. The robot comprises three structures: the handle control structure to rotate the two knobs with belt mechanisms built into an actuating chamber; a probe rotation mechanism with multiple gears actuated by a pair of motors for rotating the shaft about the long axis of the probe; and a linear belt mechanism mounted on a rail for providing linear translation of the probe and all other structures along the long axis of the probe. With these mechanisms, the probe tip where the ultrasound transducer is located can be translated, rotated, and bent bi-directionally according to a set of four robotic parameters. As human assistance is usually required for the translation axis to insert the probe and guide it down to the oesophagus, the translational axis was designed to allow both robotic and manual controls. More details of the design, along with the method of operation and safety concerns, can be found in our previous work [7]. The whole system is designed to work as an individual piece next to the surgical bed (figure 1b).

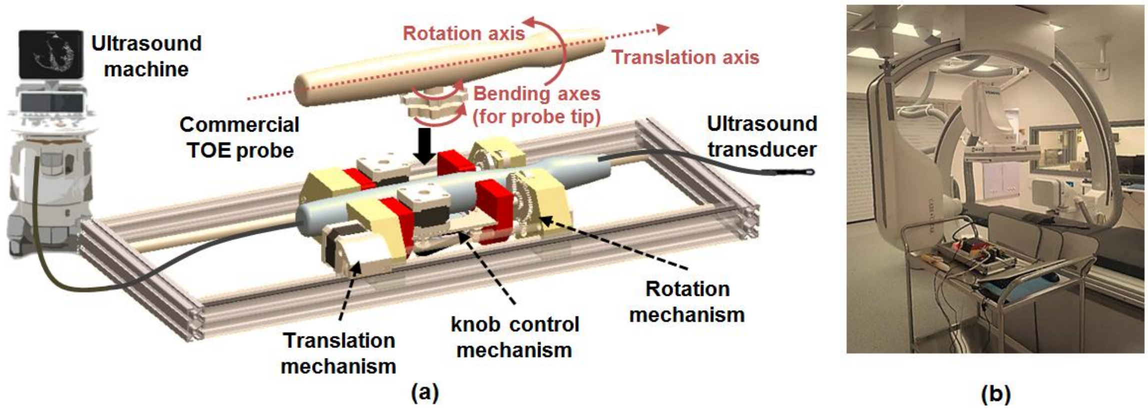

Figure 1. (a) Overview of the proposed add-on robotic 3D TOE system. (b) Possible clinical setup for the TOE robot in the surgical room with the robot sitting on a trolley.

3. Pre-planning method for initialization

The pre-planning method is intended to provide the user guidance for the initial probe positioning during a procedure. In a view-planning platform designed for pre-planning the 3D TOE view (figure 2a), an automatically segmented 3D heart model from a pre-scanned MR image, a manually segmented oesophagus centre line, and the model of the TOE probe head can be loaded and viewed intuitively. The kinematics of the probe are modelled and the corresponding virtual 2D centre slice and the cone-sized 3D volume FOV are displayed based on the given probe parameters [10]. In the platform, a number of markers representing the location of the target catheter that is to be monitored are defined from the pre-scanned MR image and used to determine the necessary monitoring range of a TOE view. The desired robotic parameters for the robotic TOE system to image the catheter are determined by the middle of the complete movement range of the catheter. This is defined as the target and its position in the ultrasound image coordinates is used for pre-planning.

An objective function based on the X- and Y-axial distances from the origin of the ultrasound image coordinates to the target is defined for the kinematics to optimize the robotic parameters using the gradient-descent search strategy based on the forward kinematics [7]. The Z-distance between the probe's transducer face and the target, measured along the Z-axis of the ultrasound image coordinates, is constrained by the heart-to-oesophagus distance and therefore the Z-distance optimization is not planned to be optimized. As reported previously, the forward kinematic model F(**p**), where **p** is the 4-DOF robotic parameter set, gives the transformation between the patient coordinates and the predicted probe tip coordinates when a heart model and the corresponding oesophagus model are given:

$$^{\mathbf{Patient}}\mathbf{T}_{\mathbf{ProbeTip}}(\mathbf{p}) = \mathrm{F}(\mathbf{p}) \tag{1}$$

The patient coordinates are defined based on the MR image coordinates. The position vector of the target defined in the patient coordinates is known as $^{\mathbf{Patient}}\mathbf{T}_{\mathbf{Target}}$. Therefore, the position of the target in the ultrasound image coordinates based on the predicted probe tip pose is calculated using a known calibration between the probe and ultrasound image [11]:

$$^{\mathbf{US}}\mathbf{T}_{\mathbf{Target}}(\mathbf{p}) = {}^{\mathbf{US}}\mathbf{T}_{\mathbf{ProbeTip}}\,{}^{\mathbf{ProbeTip}}\mathbf{T}_{\mathbf{Patient}}(\mathbf{p})\,{}^{\mathbf{Patient}}\mathbf{T}_{\mathbf{Target}} \tag{2}$$

The objective function for the search strategy is then defined based on the target position in the ultrasound image coordinates. Since both X- and Y- components of this position vector are expected to be zero to locate the target at the centre, the objective function is defined as the root sum square of the X- and Y-components extracted from $^{\mathbf{US}}\mathbf{T}_{\mathbf{Target}}(\mathbf{p})$. The search strategy for the probe robotic parameters in a defined range uses gradient-descent iteration and results in the best-fit probe robotic parameters **p*** to represent the desired probe pose $^{\mathbf{Patient}}\mathbf{T}_{\mathbf{ProbeTip}}$*****. For the initialization, 4-DOF movements are utilized giving the best-fit probe robotic parameters suggested to the user. This process is performed by the operator using the robot and the initial view will then be pointing to the approximate centre of the catheter's working range.

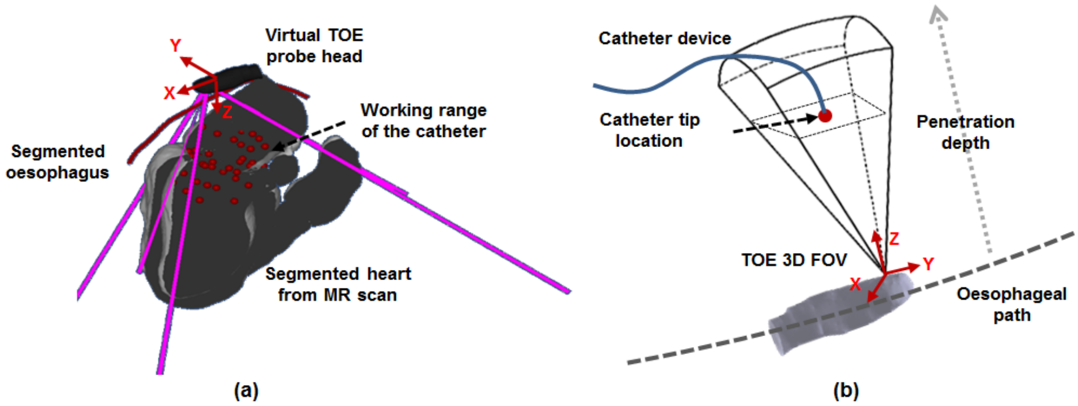

Figure 2. (a) Illustration of the strategy for probe initialization based on the pre-planning platform to locate the probe in the approximately correct region. (b) Illustration of the strategy for localized probe adjustment in order to image the device accurately in the centre of the FOV.

4. Differential kinematics for localized adjustments

For localized adjustments of the TOE probe (figure 2b) to monitor the catheter after the initialization, differential kinematics and image servoing methods are utilized to adjust the 2-DOF bi-directional bending. This starts from investigating the forward kinematics of the bi-directional bending, which has been previously described in [7]. The inputs are the rotation angle of the first bending knob, φ_x, which controls the bending tip pitch in the posterior-anterior plane; and the rotation angle of the second bending knob, φ_y, which controls the bending tip yaw in the left-right plane. The geometric illustration of TOE probe tip bending is shown in figure 3a. The translation vector and rotation matrix between the probe tip coordinates and the probe base coordinates are expressed as:

$$^{\mathbf{ProbeBase}}\mathbf{t}_{\mathbf{ProbeTip}} = \begin{bmatrix} \frac{L_f}{\beta}(1-C_\beta)C_\alpha + L_u S_\beta C_\alpha \\ \frac{L_f}{\beta}(1-C_\beta)S_\alpha + L_u S_\beta S_\alpha \\ \frac{L_f}{\beta}S_\beta + L_u C_\beta \end{bmatrix} \quad ^{\mathbf{ProbeBase}}\mathbf{R}_{\mathbf{ProbeTip}} = \begin{bmatrix} S^2{}_\alpha + C_\beta C^2{}_\alpha & -S_\alpha C_\alpha(1-C_\beta) & C_\alpha S_\beta \\ -S_\alpha C_\alpha(1-C_\beta) & C^2{}_\alpha + C_\beta S^2{}_\alpha & S_\alpha S_\beta \\ -C_\alpha S_\beta & -S_\alpha S_\beta & C_\beta \end{bmatrix} \tag{3}$$

where α is the angle between the bending plane and the X-Z plane, β is the bending angle in the bending plane, L_f is the length of the bending section of the probe tip, and L_u is the length of the rigid section of the probe tip. In the matrix, Sx and Cx, respectively, denote sin(x) and cos(x).

For the differential kinematics, the robotic joint space parameters are defined as $\mathbf{R} = [\alpha, \beta]^T$. The velocity skew of the probe tip $^{\mathbf{ProbeTip}}\mathbf{V} = [\mathbf{v}, \boldsymbol{\omega}]^T$, expressed in the probe tip coordinates, is determined by the robotic Jacobian $\mathbf{J_R} = [\mathbf{J_v}, \mathbf{J_\omega}]^T$, where $^{\mathbf{ProbeTip}}\mathbf{V} = \mathbf{J_R}\dot{\mathbf{R}}$. The resulting Jacobian is expressed as:

$$\mathbf{J_v} = \begin{bmatrix} -\frac{L_f}{\beta}S_\alpha(1-C_\beta) - L_u S_\alpha S_\beta & \frac{L_f}{\beta^2}C_\alpha(1-C_\beta) + L_u C_\alpha \\ \frac{L_f}{\beta}C_\alpha(1-C_\beta) + L_u C_\alpha S_\beta & \frac{L_f}{\beta^2}S_\alpha(1-C_\beta) + L_u S_\alpha \\ 0 & -\frac{L_f}{\beta^2}S_\beta + \frac{L_f}{\beta} \end{bmatrix} \quad \mathbf{J_\omega} = \begin{bmatrix} -C_\alpha S_\beta & -S_\alpha \\ -S_\alpha S_\beta & C_\alpha \\ -1 + C_\beta & 0 \end{bmatrix} \tag{4}$$

The image servoing control for adjusting the probe bi-directional bending pointing to the catheter can be further determined by the image Jacobian, which relates differential changes in the image features to differential changes in the configuration of the transducer, i.e. the velocity skew $^{\mathbf{ProbeTip}}\mathbf{V}$. Let $^{\mathbf{US}}\mathbf{p} = [^{US}x, ^{US}y, ^{US}z]^T$ be the tracked catheter tip position in the 3D ultrasound image space. The coordinates of the catheter tip in the probe tip coordinates $^{\mathbf{ProbeTip}}\mathbf{p}$ are decided by the fixed calibration $^{\mathbf{ProbeTip}}\mathbf{p} = {}^{\mathbf{ProbeTip}}\mathbf{T_{US}}{}^{\mathbf{US}}\mathbf{p}$. In this study, the catheter tip position is assumed to be tracked either by image-based processing methods for $^{\mathbf{US}}\mathbf{p}$ or sensor based tracking methods for both the TOE probe and the catheter, giving $^{\mathbf{ProbeTip}}\mathbf{p}$ as the result. The following relation describes the coordinates of the catheter tip in the probe base coordinate frame $^{\mathbf{ProbeBase}}\mathbf{p}$:

$$^{\mathbf{ProbeBase}}\mathbf{p} = {}^{\mathbf{ProbeBase}}\mathbf{t}_{\mathbf{ProbeTip}} + {}^{\mathbf{ProbeBase}}\mathbf{R}_{\mathbf{ProbeTip}}\,{}^{\mathbf{ProbeTip}}\mathbf{p} \tag{5}$$

As the probe shaft is not expected to move during the localized adjustment, the catheter tip is considered not moving in the probe base coordinates for a given catheter tip position when bi-directional bending is applied (oesophagus movements are ignored). The rest of the components in (5) will all change when the bi-directional bending is applied. Taking the time derivative of (5), the following relationship is obtained according to the visual servoing method summarized in [12]:

$$^{\mathbf{ProbeTip}}\dot{\mathbf{p}} = \begin{bmatrix} -\mathbf{I} & S(^{\mathbf{ProbeTip}}\mathbf{p}) \end{bmatrix} {}^{\mathbf{ProbeTip}}\mathbf{V} = \begin{bmatrix} -\mathbf{I} & S(^{\mathbf{ProbeTip}}\mathbf{p}) \end{bmatrix} \mathbf{J_R}\dot{\mathbf{R}} \tag{6}$$

where $S(^{\mathbf{ProbeTip}}\mathbf{p})$ is the skew-symmetry matrix of $^{\mathbf{ProbeTip}}\mathbf{p}$. The final Jacobian $\mathbf{J}$ relating the changes of robotic joint parameters to the changes of the catheter tip position in the probe tip coordinates is therefore obtained. With the differential kinematics, we have considered a simple controller as shown in figure 3b, where $^{\mathbf{ProbeTip}}\mathbf{P*}$ is the ideal location of the catheter in the probe tip coordinates. This can be determined in the same way as described in the previous section so that the X- and Y-components for the $^{\mathbf{US}}\mathbf{P*}$ are zero, while the Z-component remains at the same value for its current position in the ultrasound image coordinates. The corresponding desired position $^{\mathbf{ProbeTip}}\mathbf{P*}$ can then be calculated based on the fixed calibration $^{\mathbf{ProbeTip}}\mathbf{T_{US}}$ and used for the bi-directional position controller. A simple relationship then relates the resulting $\mathbf{R} = [\alpha, \beta]^T$ to the desired joint parameters.

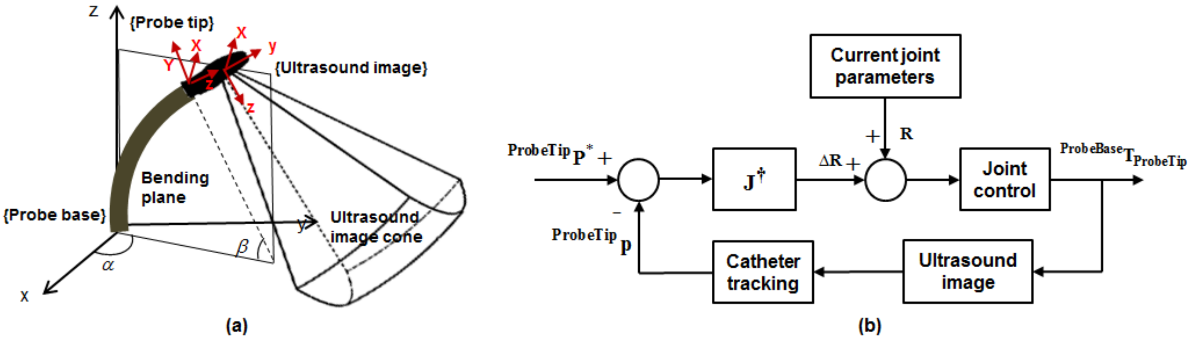

Figure 3. (a) Geometric illustration of the TOE probe tip bending with the coordinates of the probe base, probe tip, and ultrasound image shown. The probe tip coordinate frame is defined on the rigid section of the probe head (based on a Nano-CT scan) and the ultrasound image coordinate frame was defined by a fixed calibration. (b) Jacobian position control loop for localized adjustments of the probe to monitor the catheter. In the diagram, $\mathbf{J}^{\dagger}$ is the pseudo-inverse of the final Jacobian $\mathbf{J}$.

5. Simulation experiments

5.1. Positioning accuracy of the initialization method

To verify the correct working of the pre-planning strategy for the initialization step, a simulation experiment has been performed using the view-planning platform. 100 random points are defined within a heart segment obtained clinically to simulate the planned targets defined by the user. The automatic probe positioning method described in Section 3 is applied to calculate the desired probe tip pose to image the defined target, which is the centre of the catheter's moving range, at the centre of the ultrasound FOV. Based on the resulting target's position in the ultrasound image coordinates ${}^{US}\mathbf{T}_{Target}$, the error function is defined as the root sum square of the X- and Y-components extracted from the matrix. This error function quantifies the offset error from the centre of the ultrasound FOV. The evaluation indicates a mean error less than 0.5 mm for the pre-planning method.

5.2. Positioning accuracy of the Jacobian control loop

To verify the correct working of the Jacobian control loop for the localized adjustments, a simulation experiment was performed by simulating the catheter's position in the ultrasound image coordinates. Since most structures in a TOE scan are located at a depth of 5–6 cm, the Z-component ${}^{US}z$ is simulated with a random depth in this range. For the X- and Y-components indicating the catheter's movement range in the plane perpendicular to the ultrasound image penetration direction, uniformly distributed simulated positions in the range -5–5 cm were assigned. This is to cover the potential movement range based on the size of a normal heart. In the experiment, 100 target catheter positions were generated for the analysis. The corresponding resulting catheter tip positions, after applying the Jacobean control loop, were calculated and the X- and Y-components were compared with the desired values, in which case both distances are expected to be zero.

The median absolute errors of the X- and Y-components are shown in table 1 and the histogram of the absolute errors is shown in figure 4a. Since the FOV of 3D TOE extends with increasing ultrasound penetration depths, we further analyzed the centralization of the catheter tip positioning in the X–Y planes at different penetration depths taking the size of the X–Y planes into consideration. This was done by calculating the ratio of the X- and Y-components to the half-length of the X–Y plane measured along the X- and Y-axis of the live 3D TOE image coordinates. These two ratios are defined as the normalized X- and Y-distance errors. The median normalized errors were calculated and are also shown in table 1 and the histogram of the normalized errors is shown in figure 4b. For the Z-component, i.e. depth component in the ultrasound image space, the resulting mean value for the 100 simulated positions is 6.40 cm, which is within the efficient range of the TOE scan.

Table 1. Result summary for the simulation experiment using the control loop

	Absolute error (Median ±IQR)	Normalized Error (Median ±IQR)
X-axis	1.48 ±2.80 mm	4.07 ±8.51 %
Y-axis	1.02 ±3.18 mm	3.21 ±7.15 %

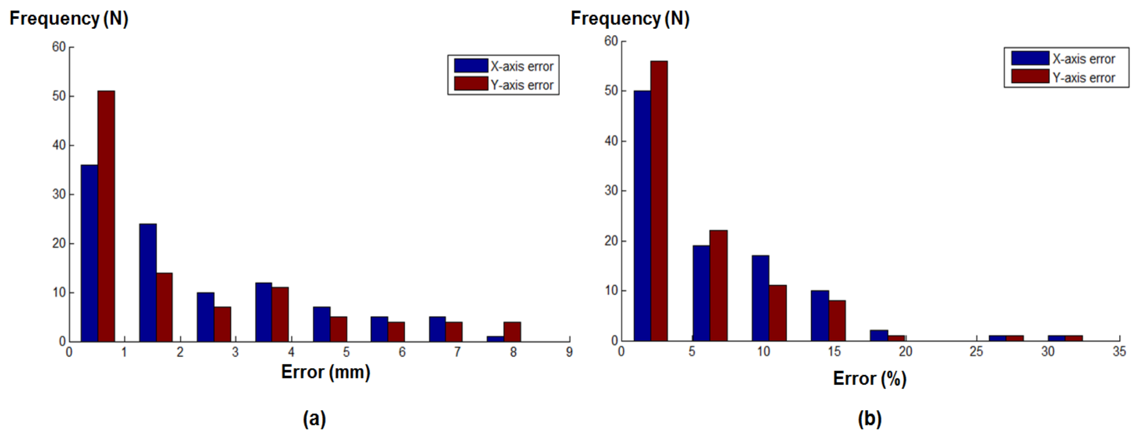

Figure 4. Histograms of the (a) absolute positioning errors and (b) the normalized positioning errors.

6. Discussion and conclusion

This paper has described a method for controlling a recently developed TOE robotic system to adjust the pose of the probe and therefore accurately monitor intra-operative catheters used in cardiac surgeries. The method has been divided into two stages with an approximate pose of the probe determined using a pre-planning method and an accurate pose of the probe adjusted based on a Jacobian position control loop. Accordingly, all of the four DOFs are employed for the once-only initialization when human assistance should be included for the probe insertion, and only two bending DOFs are utilized for the localized adjustments when the robot could be controlled automatically. In the paper, both the initialization and the localized adjustment methods have been described in detail. The results from the simulation of the initialization process indicate the correct working of the method with a submillimetre probe positioning error identified. The results from the simulation of the localized adjustment process indicate that all absolute errors are less than 2 mm as summarized in table 1 and the majority of errors are less than 1 mm as shown in figure 4a. The normalized positioning errors, as shown in table 1 and figure 4b, indicate that all catheter tip positions are located in the centre area of the FOV. Based on both results from the initialization and localized adjustments simulation, it is concluded that the proposed methods are correct and accurate for this application using the TOE probe to monitor the catheters considering the size of the FOV.

Though the simulation experiments described in this paper have verified the accurate working of the proposed methods, a number of differences between the simulation environments and the real scanning scenarios could potentially influence the performance of the methods. For the initialization, though the pre-planning method can accurately find an ideal probe pose, guiding the probe either manually or robotically to the exact location without real-time tracking of the TOE probe would be difficult. The issues for probe tracking have been discussed in detail in our previous work [10, 13] where an image-based approach and a sensor-based tracking approach were investigated. For the localized adjustments, the performances of the bi-directional bending are in reality likely to be different to the prediction of the kinematic model due to the complexities of the real environment. The tracking of the catheter, either based on an image processing technique or an additional sensor, is assumed to be known in the simulation experiments. Additionally, the catheter tip is assumed to be not moving in the probe base coordinates for a given catheter tip position when bi-directional bending is applied. It is assumed that the oesophagus's movements are negligible, while in reality this may not be true and a time-dependent oesophagus movement might need to be included into the model. With all these differences, the final performances of the methods in real scanning scenarios remain unknown. Thus, our future works will focus on developing a simple ultrasound imaging phantom to simulate the trans-oesophageal approach, allowing both the TOE probe and a catheter to work inside the phantom in order to further test the proposed methods.

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